NEIL S. ROTHMAN

VOLUME DETERMINATION USING ACOUSTIC RESONANCE

Cavities of irregular geometry can be modeled as Helmholtz resonators, provided they adhere to specific dimensional limits. If the characteristics of the entrance region or "neck" of a cavity are held fixed, the cavity's resonant frequency will be a function only of its volume. Using an electronic feedback technique and hand-held adapter, the Helmholtz resonator model has been applied to determine the volume of both simple and complex cavities, including castings of human nasal passages. Clinical application of this technique using live subjects is planned.

INTRODUCTION

Recognized as the most efficient "conditioning" region of the respiratory tract, the nasal cavity serves to filter particles, absorb toxic or pollutant gases, and heat and humidify inspired air. The degree of nasal cavity conditioning determines the lung exposure to inhaled agents. The geometry of the nasal cavity—and therefore its conditioning "efficiency"—varies, depending on the vascular state of the nasal turbinates. The turbinates are erectile tissues that respond to cold, exercise, and pathology. The consequent changes in nasal volume and surface area have never been quantified, although their effect on conditioning efficiency has been documented.

The measurement of nasal cavity geometry in humans is difficult. Volume-determination techniques that require filling the cavity with fluid are both uncomfortable for the patient and prone to errors if fluid is absorbed or leaks from the cavity. In addition, the properties of the fluid (e.g., temperature) can alter the state of the turbinates, and thereby the volume. The human nasal cavities control the flow of inspired air for optimal conditioning. Their convoluted geometry (Fig. 1), however, makes simple, direct dimensional measurement difficult. Data obtained using cadavers are only of qualitative value, since changes in the state of the turbinates and other tissues resulting from death or preservation agents are unknown. Approximation techniques using simplified geometry are not sufficiently accurate to be useful. Therefore, a noninvasive or minimally invasive technique capable of quantifying the volume (and surface area, if possible) of the nasal cavities would enhance the investigation of normal variations in nasal cavity geometry and of the effects of various stimuli on the conditions of the upper respiratory airways.

HELMHOLTZ RESONATOR THEORY

Lumped parameter models are used to analyze the dynamic characteristics of mechanical systems by substituting masses, springs, and dampers for the individual components of the system. The application of forcing functions to specific points in the model elicits responses that can be used to predict the behavior of the original

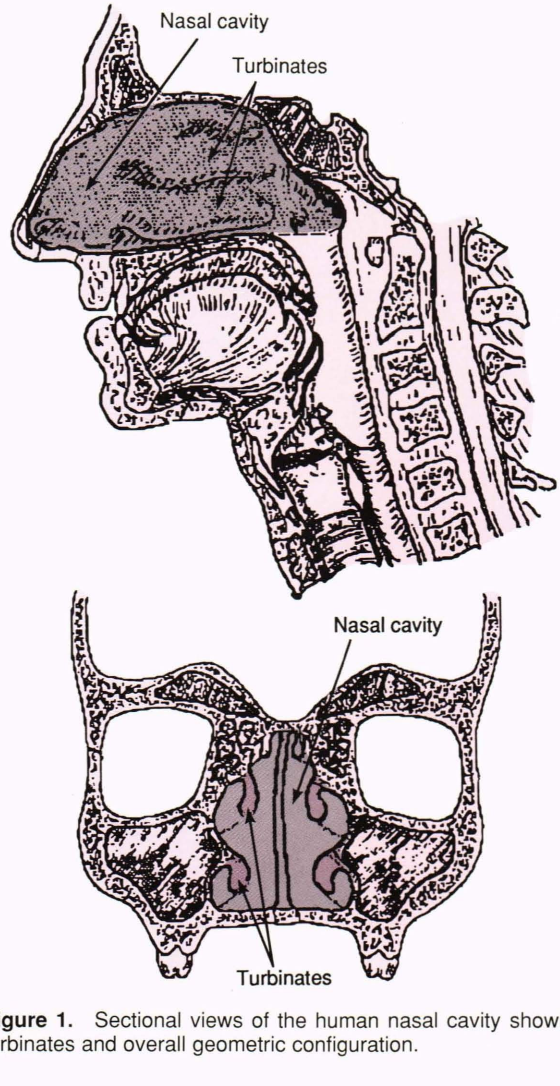


Figure 1. Sectional views of the human nasal cavity showing turbinates and overall geometric configuration.

system. Similarly, the response of a cavity to acoustic inputs can be predicted by using an acoustic lumped-parameter model, the Helmholtz resonator model. This predictive approximation, assumed to be applicable to cavities such as the human nasal passages, not only characterizes a cavity's acoustic behavior, but also can be used to determine its volume.

The Helmholtz resonator is a chamber of a given volume, connected to its surroundings via an entrance region or "neck." Analogous to a one-degree-of-freedom spring-and-mass mechanical lumped-parameter model, it is characterized by a resonant frequency that is a function of the cavity volume and inlet configuration but independent of its actual geometry. Kinsler and Frey[1] found that "As long as the linear dimensions of the cavity are considerably less than a quarter wavelength and the opening is not too large, the resonant frequencies of cavities having the same opening and volume but having very different shapes are found to be identical." A schematic model and the pertinent equations for a Helmholtz resonator are shown in Figure 2.

If the neck of a Helmholtz resonator is held fixed, its resonant frequency will shift only in response to volume changes. Therefore, by measuring the resonant frequency of the cavity, the volume of the cavity can be predicted. Deskins et al.[2] used this theoretical approach to predict the behavior of an acoustic plethysmograph for measuring infant body volume. Rearranging the equation for the resonant frequency of a Helmholtz resonator and collecting the neck configuration terms into a constant, K, we obtain the following:

$$V = K/f^2 \ ,$$

where V is the volume and f is the resonant frequency. The neck geometry appears in the Helmholtz resonator equations not only through the neck's physical dimensions, but also through a correction factor to its length, which is a function of the end configuration of the neck. For the present neck design, the correction factor is best approximated by $\pi a/2$, where a is the neck radius. For other configurations, however, where a formula for this factor does not exist, it has to be determined empirically. Once the correction factor is known, the volume of the constant K can easily be found. Alternatively, calibration using known volumes eliminates the intermediate step and provides K directly. The resulting equation represents the theoretical basis for predicting volume from resonant-frequency measurements. Its applicability to convoluted cavities such as the nasal passages, however, required investigation.

EXPERIMENTAL VALIDATION

To test the application of the theory just discussed, a simple cylindrical cavity was used. A 9.5-mm-diameter electret microphone was connected to the cavity with a small (1.0-mm inner diameter) tube to minimize its effect on the cavity's behavior. A loudspeaker, driven by a signal generator, was suspended above the neck of the cavity, and the output of the microphone was sent to a sound-level meter. By rotating the frequency selector dial on the signal generator, the frequency at which the acoustic response of the cavity was a maximum—its resonant frequency—could readily be found. An external frequency counter was used for the best possible accuracy in determining the resonant frequency. Inaccuracies resulted, however, from operator error in finding the resonant peak and from poor resolution of the signal generator controls. An alternative technique for determining the cavity's resonant frequency was required.

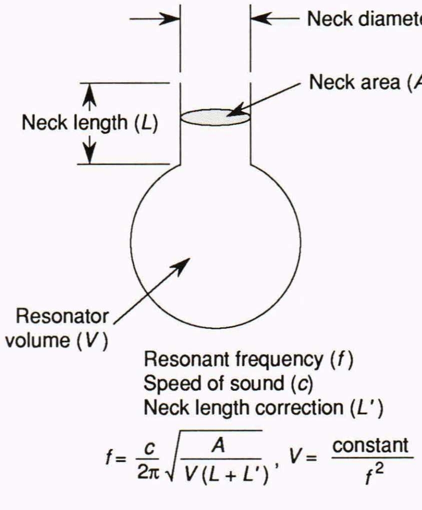


Figure 2. Schematic diagram of a Helmholtz resonator and the pertinent equations for predicting resonant frequency from cavity geometry.

The frequency-response spectrum of the entire system can provide the same information as the single resonant frequency for the cavity. Using a white-noise generator to drive the loudspeaker and a spectrum analyzer connected to the output from the microphone, the entire frequency-response spectrum for the system was established and displayed on the spectrum analyzer screen. A block diagram of the system is shown in Figure 3. This technique was applied to test cavities, and the response spectra were plotted on an x–y plotter. The technique proved more accurate and repeatable and easier than the manual frequency sweep technique, in determining the resonant frequency of the cavity. The frequency-dependent characteristics of the test equipment were identified and discarded by comparing successive spectra. Typical measured frequency-response spectra are shown in Figure 4. Evident in these plots is a system resonance—a peak in the frequency response of a component of the test equipment in the circuit. Such a peak is identified easily since it does not change with the cavity volume. In Figure 4, the system resonance is most probably due to the loudspeaker.

Small, cylindrical plastic cavities, about 15 cm^3 in volume, were fabricated specifically to validate and test the limits of the acoustic theory. Their initial volumes were determined accurately by differential weighing before and after filling with water. The cavities were used

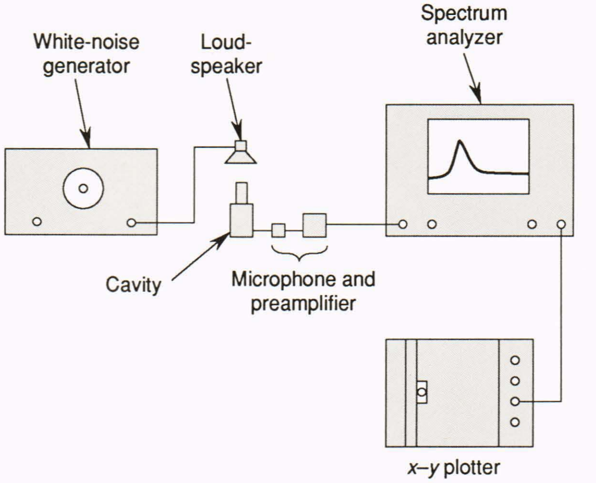


Figure 3. Block diagram of the white-noise excitation system for determining the entire frequency-response spectrum for a cavity.

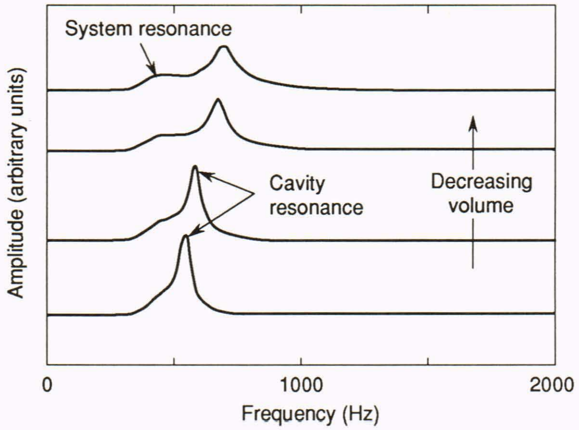


Figure 4. Plot of typical frequency-response spectra for white-noise excitation. The shift of the resonant frequency with volume is clear from the successive traces.

to test the acoustic theory over a wide volume range by adopting the following procedure: (1) the resonant frequency of each cavity was determined; (2) water or precision stainless steel balls were added to each cavity to alter both its internal geometry and its volume; and (3) the resonant frequency was again found. These steps were repeated until the cavities were full.

Water and stainless steel balls were used to allow differentiation between the effects, if any, of volume change and complexity of cavity geometry. During water addition, the cavity remained cylindrical; with the random packing of spheres, the test cavity became significantly convoluted.

The results of the calibration tests and theoretical predictions are plotted in Figure 5. The theory predicted the volume to better than ±5% over the volume range used. This successful volume prediction in test cavities with volumes and configurations comparable to human nasal passages provided confidence that the technique

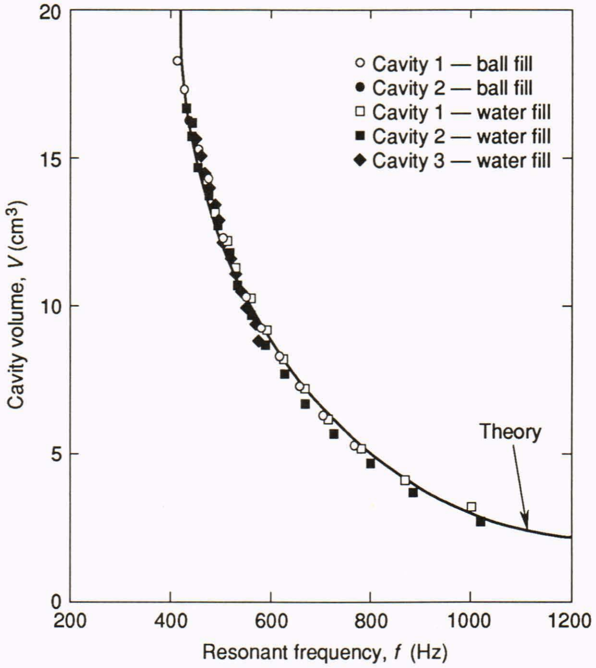


Figure 5. Frequency–volume data from initial validation tests using cylindrical test cavities.

could be extended for volume measurement of actual human nasal cavities.

NASAL CAVITY MEASUREMENTS

Specialized instrumentation had to be developed to allow use of the system with numerous subjects. A handheld adapter containing a miniature loudspeaker and a connection for the electret microphone was designed and fabricated. It sealed the nostril and provided a well-defined and constant neck. Calibration of this system with a single cavity thereby provides all the necessary data for its use with many subjects.

D. C. Winter found that swept-frequency, white-noise excitation or similar direct-excitation techniques relied on the resonance factor, Q, of the cavity to provide sufficient acoustic signal strength to allow resonant frequency determination (personal communication, 1988). In a larger cavity or in one with significant acoustic absorption (such as the human nasal cavity), the Q is probably so small that this type of measurement technique will not work. An improved technique had to be found. An electronic feedback system patterned after the acoustic plethysmograph in Ref. 2 was built for our measurements.

The electronic feedback system consists of the adapter previously described, a preamplifier, a tracking filter, and a frequency counter. The output of the microphone goes to a preamplifier and then to the input of the tracking filter. The output of the tracking filter is connected back to the loudspeaker, forming an acoustically modulated loop (see Fig. 6). The ambient noise in the cavity is picked up by the microphone. Since the cavity (resonator) selectively emphasizes its resonant frequency in the microphone signal, the tracking filter locks onto the reso-

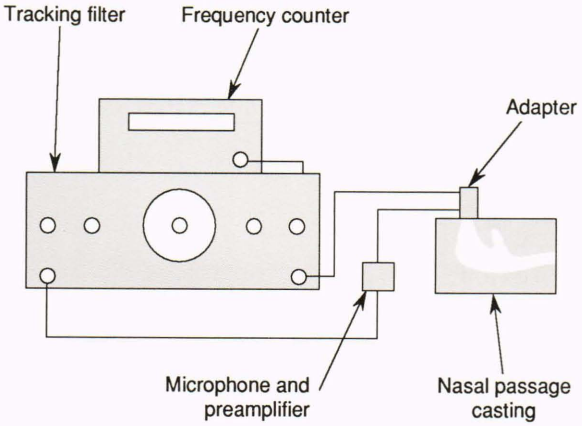


Figure 6. Block diagram of the electronic feedback system.

nance. The output of the filter, connected to the speaker, drives the cavity at its resonant frequency. When the gain of this system is sufficient for the tracking filter to lock onto the cavity resonance, the system oscillates at that frequency. The frequency counter is connected to the back panel of the tracking filter and displays the center frequency of the filter as it searches for and locks onto the resonance (Fig. 7).

Left- and right-hand castings of the nasal cavity from a human cadaver were used to test the predictive capabilities of the new electronic system on anatomically realistic cavity geometry (Fig. 8). Actual cavity volumes were again determined by differential weighing before and after filling with water; water and Teflon balls were used to modify the cavity volume as before. (These cavities were significantly larger than the previous test cavities but still adhered to the required dimensional constraints for modeling as Helmholtz resonators.) The nasal cavity was sealed with clay to simulate closure of the back of the nasal cavity by the soft palate. The adapter was sealed to the castings with a compliant gasket material, as shown in Figure 9.

The results of these measurements, plotted in Figure 10, show a shift of the measured data from theory, probably resulting from two factors: phase shift and system resonances.

The strength of this feedback technique is its relative insensitivity to the Q of the acoustic cavity, as compared with the previously described direct-excitation techniques. The frequency of the oscillation, however, is susceptible to influence by each component in the circuit. For example, the phase-locked loop of the tracking filter introduces a 90° phase lag into the acoustic signal, which causes the loudspeaker (filter output) to drive the cavity with a signal that lags 90° behind the existing acoustic oscillation in the cavity. This lag causes the apparent period of the oscillation to increase, reducing the frequency tracked by the filter. The effect is clearly evident in Figure 10. The complex impedances of the microphone and loudspeaker will also introduce phase shifts into the feedback loop.

Each element of the electronic circuit also has a frequency-response characteristic. When the tracking filter finds one of the component resonances, such as a peak in the response of the loudspeaker or microphone, it may lock onto that frequency instead of the cavity resonance. If close enough in frequency, a component resonance may obscure the cavity resonance. A system component resonance can typically be differentiated from a true resonance, however, since it persists after the adapter is removed from the cavity; for a true resonance, once the seal to the cavity is broken, the oscillation stops.

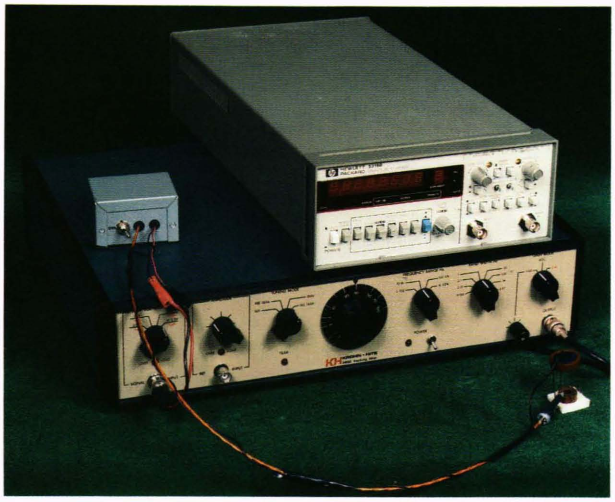


Figure 7. Photograph of the electronic feedback system showing the hand-held adapter and other system components.

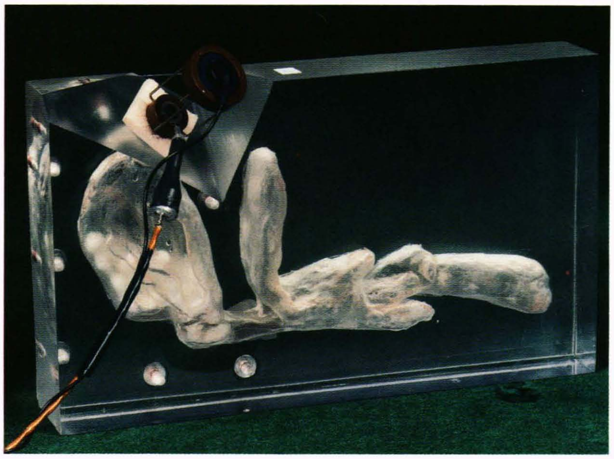


Figure 8. Nasal cavity casting with adapter in place for resonant-frequency measurements.

To eliminate such phantom-resonance errors, which are consistent from trial to trial, an empirical approach was taken to fit the data to the theory (i.e., to determine the constant K in the equation for the volume). By iterating the constant, assuming a linear relationship between the volume and the inverse square of the frequency, the fit of the data was significantly improved (Fig. 11). A discrepancy still exists in the fit at small volumes, however. This discrepancy is an artifact resulting from the techniques used to modify the cavity volumes.

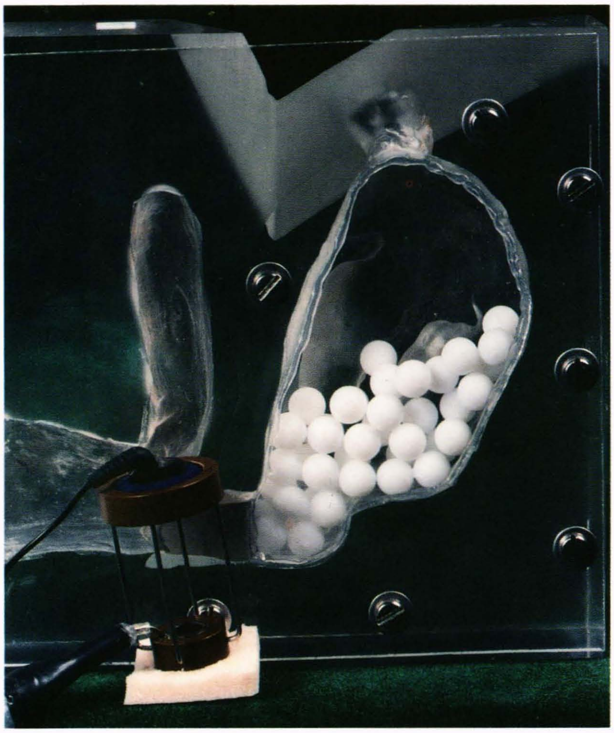


Figure 9. Nasal cavity casting partially filled with balls to illustrate the complex geometry of the residual volume.

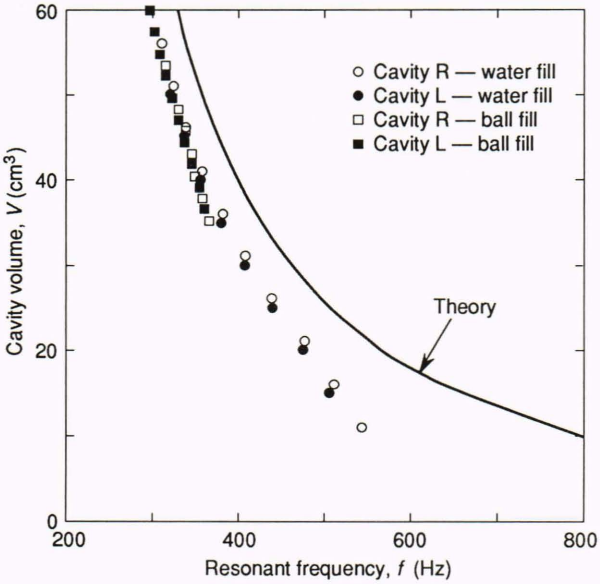


Figure 10. Initial results from feedback system measurements on nasal cavity castings.

As a Helmholtz resonator oscillates, the air in the neck moves in and out, just like a mass on a spring. This moving volume of air extends into and out of the cavity volume. As the cavity volume is reduced by filling it with water or balls, the surface of the balls or water nearest the neck is approached by the moving air volume. At some point, interference occurs, causing the measured frequency to be lower than predicted by the theory, hence the artifact in the data. Since this geometric effect results from trying to obtain data over a very wide volume range and is not anatomically valid, we will not correct for it here. With the system calibrated, then, we should be able to make volume predictions from resonant-frequency measurements in intact human nasal cavities with reasonable accuracy.

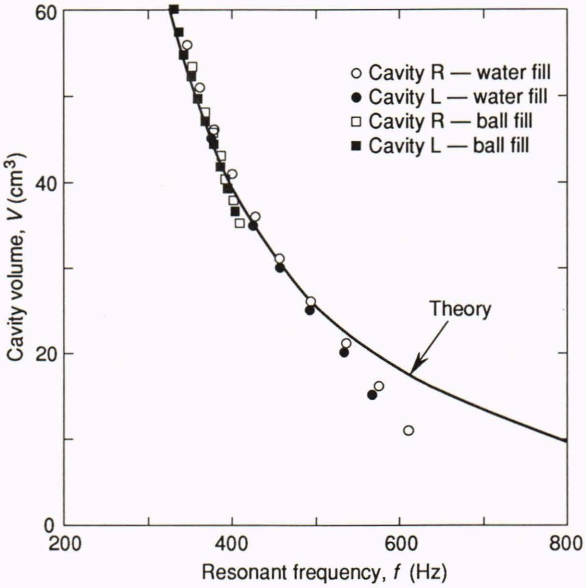


Figure 11. Modified theoretical prediction based on an empirical fit to the data.

DISCUSSION

A noninvasive method for determining the volumes of cavities of irregular geometry was developed, and theoretical predictions were validated with experimental results. In addition to the tests run with the castings and cavities described in this article, trial measurements on the investigators have been attempted. Difficulties have been encountered with these measurements, principally because of errors in the assumption that the intact human nasal cavity can be modeled as a Helmholtz resonator.

The Helmholtz resonator theory is derived for a rigid cavity whose only communication with the exterior is through the neck. For the nasal cavity, not only is the cavity surface not rigid, but side branches into the sinuses may have resonances of their own and may affect the measurements. In addition, the anatomy of the nasal cavity is such that it is open to the throat except during swallowing. While a person breathes through the mouth, air still moves through the nasal passages. For volume measurements using our technique, the cavity must be closed except at the neck. Unless the person being measured can voluntarily close the soft palate at the back of the throat, the cavity will not resonate and its volume cannot be measured. Also, if the closing of the cavity is not consistent (i.e., if the actual volume varies from time to time), the measurement will not be repeatable. Cavity volumes including some unknown portion of the throat may also result. Lastly, a normal cyclic variation in the state of the turbinates may preclude repeatable measurements. Abnormal or prolonged sealing of the cavity may also affect volume.

Despite these problems, our technique has promise as a noninvasive method for determining the actual volume of the human nasal cavity *in vivo*. Patient training before volume measurement or artificial means for closing the nasal cavity will most likely be required to obtain repeatable and accurate results. In the near future, we will couple our technique with magnetic resonance imaging (and image-processing techniques) to validate the measurements taken with human subjects.

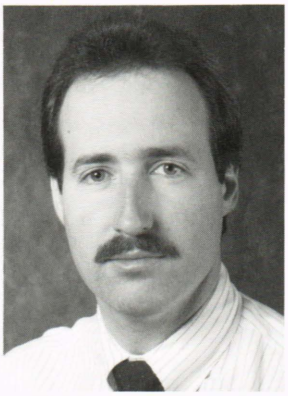
REFERENCES

[1] Kinsler, L. E., and Frey, A. R., *Fundamentals of Acoustics*, John Wiley & Sons (1962).

[2] Deskins, W. G., Winter, D. C., Sheng, H.–P., and Garza, C., "An Acoustic Plethysmograph to Measure Total Infant Body Volume," *J. Biomechan. Eng.* **107**, 304–308 (1985).

ACKNOWLEDGMENTS: This work was supported in part by a grant from the Whitaker Foundation to Linda Hanna of The Johns Hopkins University School of Hygiene.

THE AUTHOR



NEIL S. ROTHMAN received his B.S. in biomedical engineering and M.S. in mechanical engineering from Rensselaer Polytechnic Institute, and is presently a candidate for a Ph.D. in mechanical engineering from The Johns Hopkins University. He joined APL in 1983 and was promoted to Senior Staff in 1987. Mr. Rothman has been Section Supervisor of the Mechanical Analysis and Design Section of the TED Group for three years. He is a member of the Laboratory's Biomedical Devices Committee and was awarded the 1990-91 Merle Tuve Fellowship to pursue research interests in the measurement of myocardial wall stress at the Johns Hopkins Hospital.